Transmission Topology Control Algorithms (TCA) for Infrastructure Resilience to the Integration of Renewable Generation

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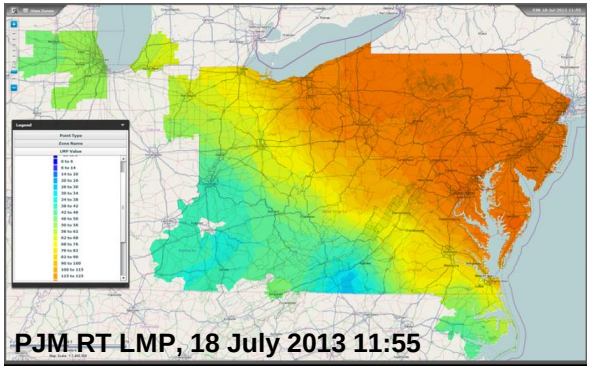
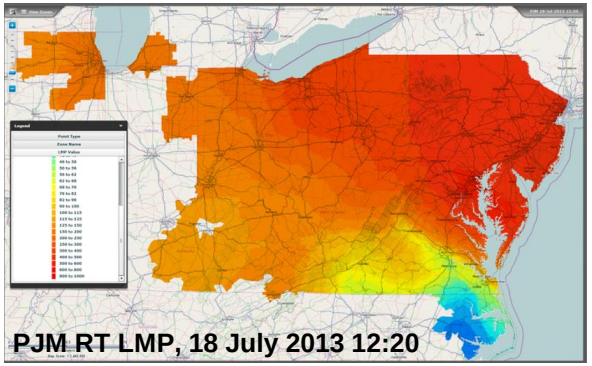
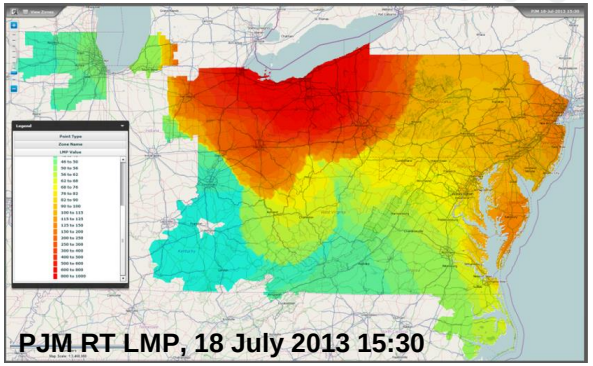
Project Objectives







Objectives: *Develop technology to enable fast identification of beneficial transmission grid reconfiguration to support operations decision making.*

- Extract more value out of existing and new transmission capacity.
- Provide additional controls to manage congestion.
- Significantly lower generation costs.
- Enable higher levels of variable renewable penetration.

Evaluation: *Simulations on detailed operational models of the PJM real-time and day-ahead markets.*

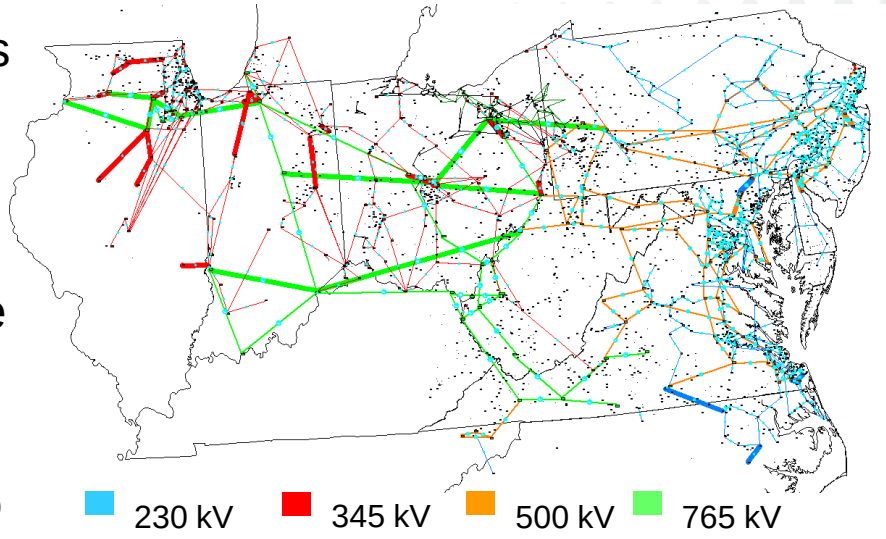
Approach: *Target applications are days-ahead through real-time decision processes.*

- Focus on tractability, aiming at providing good topologies quickly, consistent with power market needs.
- Solution performance is enabled by smart use of sensitivity information and efficient MIP TC formulations.
- Efficient contingency analysis, stability and topology evaluation ensure reliable and secure solutions.

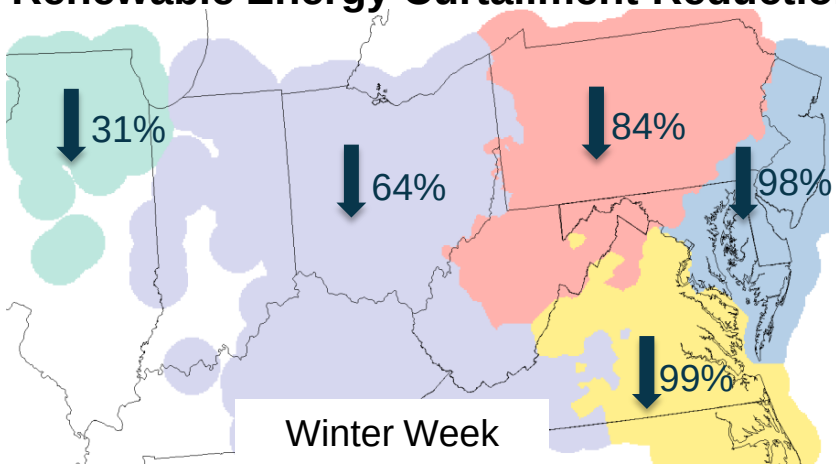
TC in a High-Renewables World

Final Year Accomplishments

- *Hybrid* historical-high renewables cases
  - One power flow snapshot per hour for three representative historical weeks in 2010 (one per season)
- Renewables data from PJM Renewable Integration Study 30% Low Off-shore Best sites On-shore Scenario
  - Current penetration level below 3%
- Transmission expansion taken from the same PRIS scenario
- Renewable curtailments were reduced on average by 40% (some of the remaining curtailments were not due to transmission constraints, but due to min gen constraints)



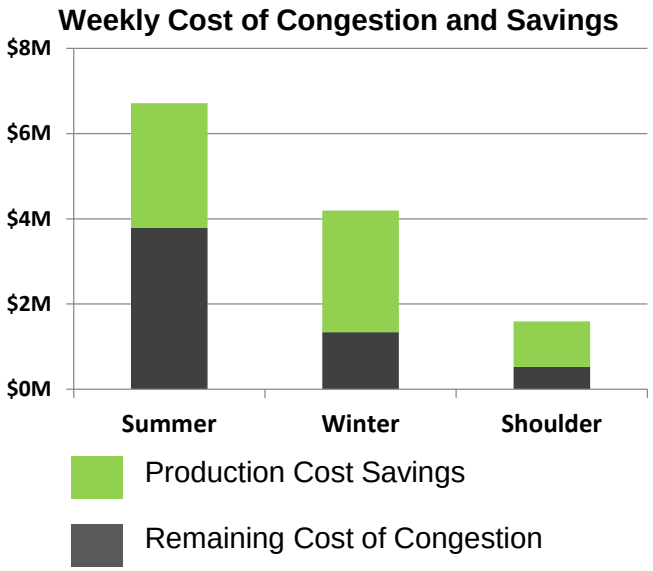
Renewable Energy Curtailment Reduction



Topology Control on AC Cases

Final Year Accomplishments

- Initial analysis in Years 1 and 2 was based on DC assumptions
- Sequential optimization of linear models obtained around AC solution points
- *Production Cost Savings* = production cost without TCA (historical topology)
  – production costs with TCA
- *Cost of Congestion* = production cost with transmission constraints
  – production costs without transmission constraints
  - The Cost of Congestion is an upper bound on the maximum savings attainable with *any* transmission efficiency technology.
- Algorithm Criteria
  - Solution time: 5 minutes time limit for each interval solution.
  - Cost of switching: $200 per open/close breaker operation.
  - Reliability: linearized cont. analysis and voltage constraints.
- **Estimated annual production cost savings in PJM RT markets under 2010 conditions are *over $100 million.***
  - Based on simulation results for three historical weeks.
  - Savings of over 50% of Cost of Congestion.

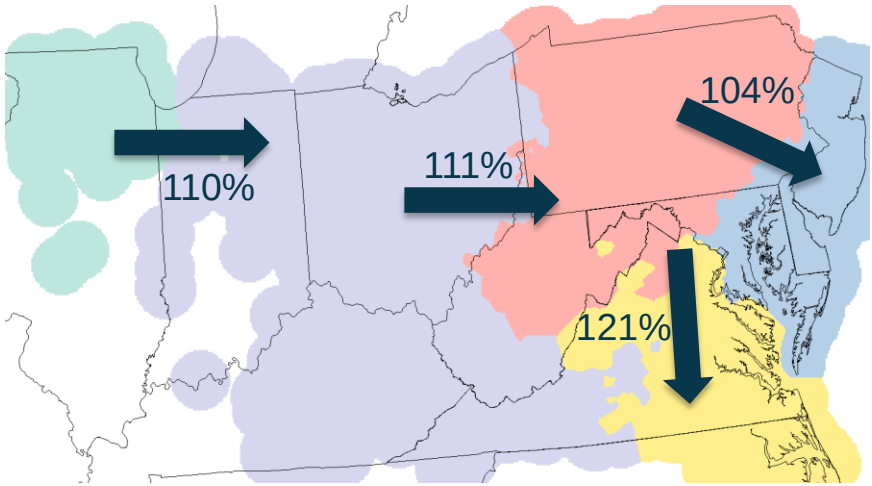


TC on AC Cases – Ops Statistics

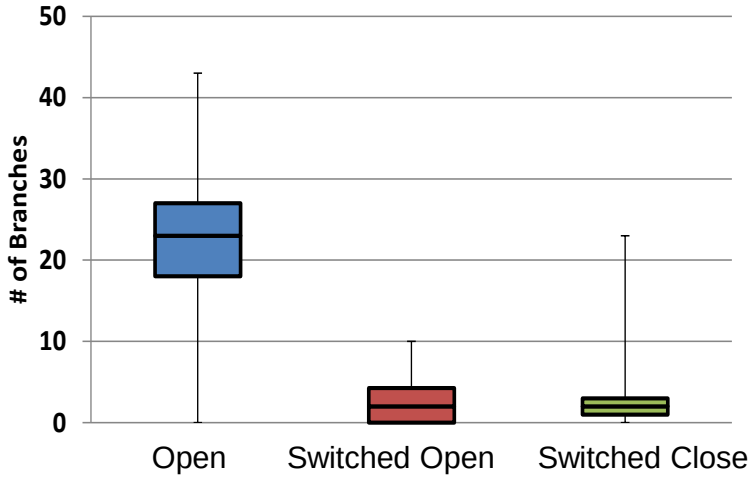
Final Year Accomplishments

2010 Summer Average Conditions

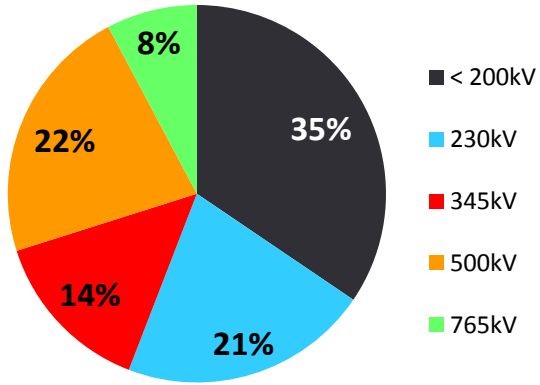
Change in Weekly Energy Transfers



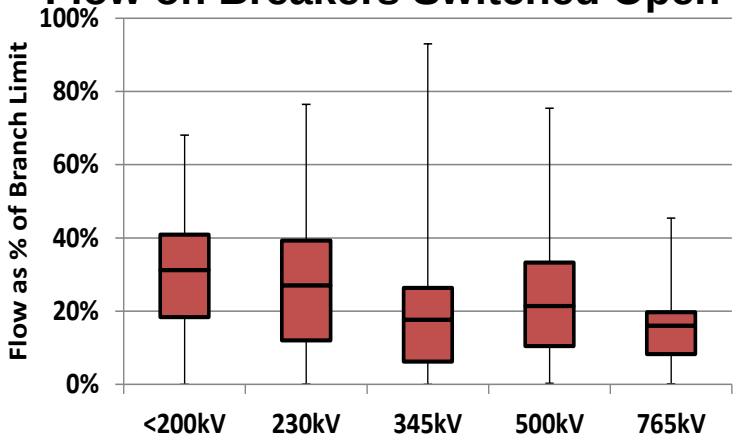
Topology Change Statistics



Breaker Operations by Voltage Level

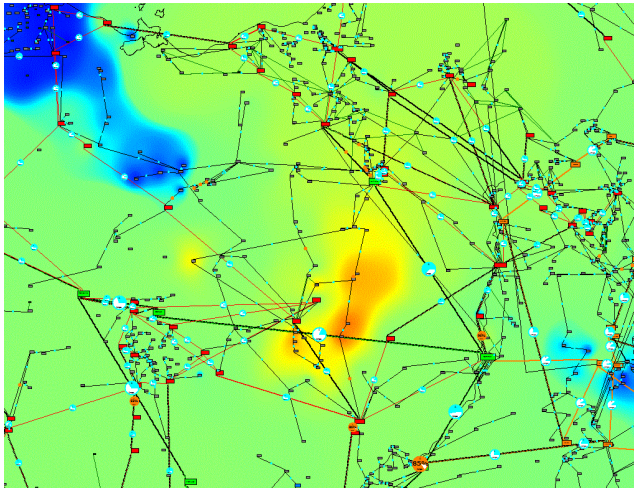


Flow on Breakers Switched Open



Breaker-Node and Fast CA

- Developed capabilities to use full breaker-node models and identify topology reconfigurations in terms of breakers status changes
- Tested capabilities by simulating a 300 MW overload on an important contingency constraint of a 500 kV branch by reducing the facility rating on a recent (July 2014) system snapshot
  - TCA identified a collection of potential switching solutions, which included between 1 and 5 switching actions
  - The potential solutions were tested by RTO staff on the EMS model; some solutions were able to relieve the overload without causing other post- or pre-contingency violations



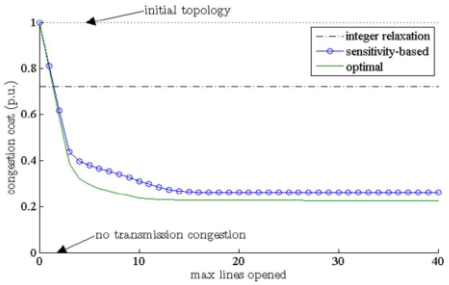
- Developed an extra-fast linearized contingency analysis tool that runs on a GPUs (~50x faster than commercial CA tool running on a multi-core CPU with similar cost as the GPU)

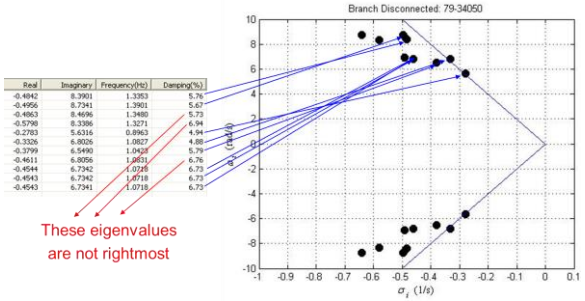
TC with UC and Voltage Stability

- Finish development, testing and benefit evaluation of algorithms for co-optimization of topology and unit commitment
  - Preliminary results indicate savings about double as compared to the topology control problem without unit commitment decisions
  - Target of over $200 million in annual production cost savings (PJM 2010)
- Develop and implement voltage stability evaluation algorithms
  - Capable of incorporating dynamic aspects such as distance to oscillatory instability
  - Use algorithms to characterize sensitivity of voltage stability indicators on load voltage dependence
- Tighter integration of some reliability routines with optimization routines
  - Contingency analysis on GPU
  - Voltage stability evaluation

Algorithms and Implementation

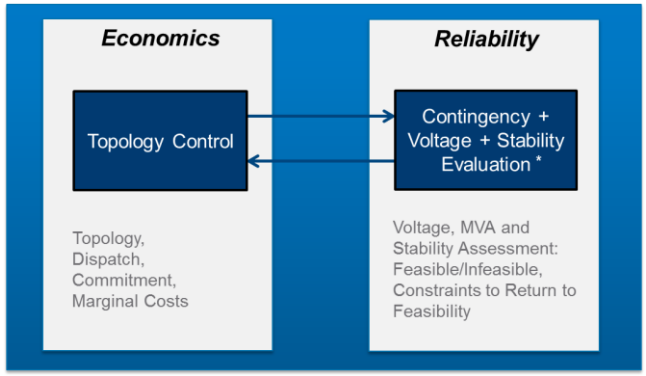
- Developed tractable topology control algorithms using sensitivity-based heuristics and a reduced MIP formulation of the TC problem. Practical solution times reached (below 5 minutes in PJM).





- Designed and implemented approaches for fast reliability evaluation (small-signal stability and contingency analysis), including fast model initialization with dynamic state estimators, dynamic model reduction, and generation dispatch constraints to ensure stability.

- Algorithms implemented in PSO, Matlab, PowerWorld and DSA Tools using an iterative structure similar to those used by market clearing software (solution of smaller optimization problem and verification of reliability constraints).



Large System Models

Characteristics

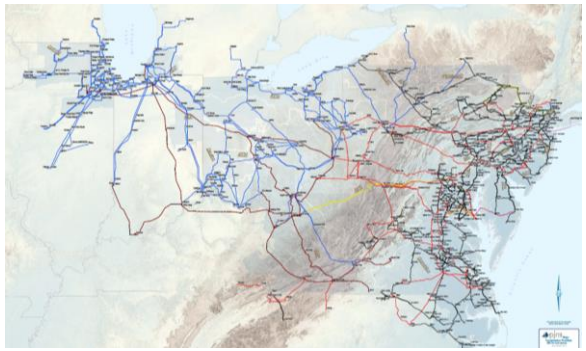
- PJM day-ahead + real-time simulation.
- Based on historical data (2010, 2013, 2014).
  - Generation economics.
  - Must-run, maintenance and outage schedules.
  - Load profiles and forecasts.
  - Reserve requirements.
  - Operational power flows (inc. historical topology).
  - Interchange with neighboring regions.
  - Transmission constraints and contingencies.
- Models approximate magnitudes.
  - Over 13,000 nodes (up-to 100k for breaker node).
  - Over 18,000 branches.
  - Over 6000 single and multi-element contingencies.

Three Sets of Models

Used representative historical instances to model.

- Average historical conditions.
  - Summer, winter and shoulder weeks from 2010.
  - Benchmarked both DA and RT market results against historical data (nodal prices (major trading hubs), dispatched generation mix, congestion costs and congestion patterns).
- Recent summer peak conditions.
  - Useful to obtain feedback from operations.
  - Summer peak week from 2013.
  - Summer peak snapshot from 2014 w/ EMS detail
- High renewables conditions (previous slides).

Models results reviewed by PJM experts.



- Comprehensive models are an invaluable tool to test and develop algorithms.
- Very significant effort needed to put them together and benchmark them.

Technology Dissemination

Technology to Market

- Papers and Presentations
  - IEEE PES Super Sessions 2013 and 2014
  - FERC Tech Conferences 2012, 2013 and 2014
  - Allerton Conference 2012 and 2013
  - HICSS 2012, 2014 and 2015
  - EPRI Grid Operations and Planning Advisory Committee 2013
  - UVIG Workshops 2013 and 2014
  - PowerTech 2013
  - NAPS 2013
  - IEEE Transactions on Power Systems (2 papers)
- Utility visits / presentations
  - Most RTOs in North America
  - Several market participants
  - There is overall interest from the industry
- International Visitors / Presentations
  - Russian Grids Company
  - Japanese Science and Technology Agency
  - Buenos Aires (Argentina) Grid Operator
- November 2013 PJM Hosted Industry Meeting (joint with RATC)
  - 50 + Attendees from ISOs, utilities, suppliers and FERC

Commercial Objectives

- TCA Applications
  - Co-optimization of transmission topology with resource dispatch
  - Overload relief in operations
  - Outage scheduling support
  - Contingency planning support
- Commercial Objectives
  - Market consulting services with TCA to ISOs, utilities and government agencies and regulators.
  - License technology to develop commercial packages to support current RTO and utility decision processes
  - License TCA to or through EMS vendors into next generation of EMS investments by ISO and TSOs.
- Important milestone events going forward
  - Finalize IP agreements
  - Empower consulting entities to market TCA
  - CEs to market / implement Outage Scheduling evaluation system

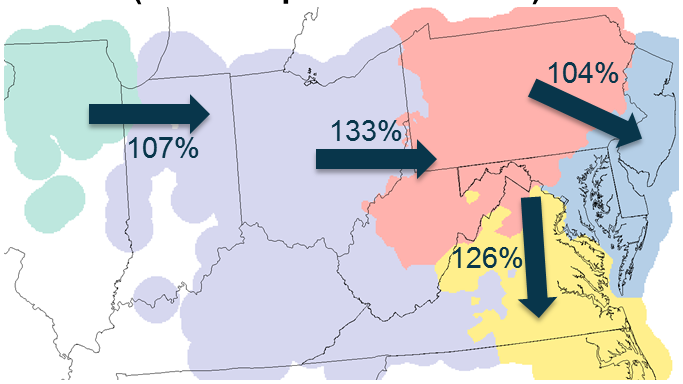
Post ARPA-E Goals

- Two parallel efforts.
  - Tools development, commercialization and deployment in RTOs, and technology licensing.
  - Consulting engagements to support TC deployment and further development.
    - Understanding commercial value of implementation of TC.
    - Market design and policy aspects.
- Funding for further tool development will be generated internally from corporate team members as well as externally from industry sources.
- Initial technology deployment will focus on established processes that do not require market rule modifications.
- Large-scale use of TC in power markets, with optimization of topology in the market clearing processes, may require market design changes.
  - Example: modification of FTR market rules.
  - Market design changes will have to go through the stakeholder process, taking significant time and effort.

Concluding Remarks

- The TCA project will provide practical technology to enable transparent, consistent and routine implementation of topology control with significant efficiency and reliability gains.
- Lessons from the PJM market evaluation:
  - Hourly security-constrained TCA solutions are obtained in only a few minutes.
  - Simulations on detailed PJM RT market models indicate that annual PJM savings are over $100 million (under 2010 conditions).
  - Consistent savings of over 50% the estimated total costs of congestion observed across all market conditions (seasonal and load levels).
  - Impacts of co-optimized topology and unit commitment on DA markets are expected to be significantly larger.
- TCA technology can be readily deployed to assist with some business processes, but would require market rule changes for wide-scale use to attain it's full potential value.

Transfer between PJM Regions with TCA (summer peak conditions)



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